Disease transmission via drops and bubbles

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Watery air bubbles covered with bacteria or viruses can live far longer than uncontaminated ones. And on bursting, they spawn orders of magnitude more droplets, each one a microbial grenade.

Seasonal influenza was responsible for nearly a million hospitalizations in the US in 2018, and tuberculosis killed more than a million people around the world. Those and other infectious diseases are spread by pathogens, such as bacteria and viruses. An important part of the pathogens' life cycle occurs in liquids, whose fluid dynamics influences transmission from one infected host or environmental reservoir to another.

A cough or sneeze, for instance, produces a turbulent cloud of hot, moist air and droplets, as shown in figure 1. That cloud and its droplet payload can span a room up to 8 m long in a few seconds. Droplets can also be spread from bursting bubbles or splashed from a wet, contaminated surface.

To predict and model disease transmission at both population and individual scales, and to develop efficient mitigation innovations and strategies against the spread of infectious diseases, understanding the role of the underlying fluid dynamics is critical. Yet little is known about the factors affecting the source, transport, and persistence of pathogen-bearing droplets. This Quick Study focuses on the example of bursting air bubbles to illustrate the rich physics and close coupling of biology and fluid dynamics in the context of disease transmission.

Bursting bubbles and droplets

Watery air bubbles are ubiquitous: They populate the surfaces of pools, rain puddles, and wastewater treatment plants, and an estimated 10^{19} bubbles are created every second in Earth's oceans and seas. As they burst under various conditions, each bubble can emit hundreds of water droplets. Those droplets are efficient vehicles for transporting what the water contains, including microorganisms, toxins, and even crude oil. Bursting bubbles from a flushing toilet can send droplets more than a meter into the air. They are also easily carried aloft by winds, over both short and long distances.

A surface bubble consists of a thin cap of water a few microns thick that entraps air. The curvature of the cap creates an overpressure relative to the bulk water below it. To first order, the pressure difference induces a flow resisted by viscosity at the base of the bubble. The cap drains into the pool of water it is connected to, and its thickness continuously decreases until the bubble eventually ruptures and ejects droplets.

Figure 2 illustrates an important factor governing the properties of those droplets: the thickness of the cap when it bursts. Thinner bubbles emit more, smaller, and faster-moving droplets than do thicker bubbles. It follows that older bubbles generate droplets that are particularly efficient at spreading contaminants because they are smaller and more easily transported longer distances.

During our experiments at MIT, we noticed that the bubbles on the surface of clean, distilled, bottled, or tap water burst quickly, typically within a couple of seconds; fewer than 5% survive up to 10 seconds. But even during that short lifetime, their interaction with the ambient air can control their thickness in a surprising and counterintuitive way. In addition to draining, the water in a bubble also evaporates. By cooling the bubble's cap, evaporation increases its surface tension compared with that of the bubble's base, which remains at ambient temperature.

The imbalance in surface tension drives water from the base (low surface tension $\sigma-$) toward the cap (high surface tension $\sigma+$), a phenomenon known as Marangoni flow. The upward flow counteracts the drainage and produces thicker bubbles of

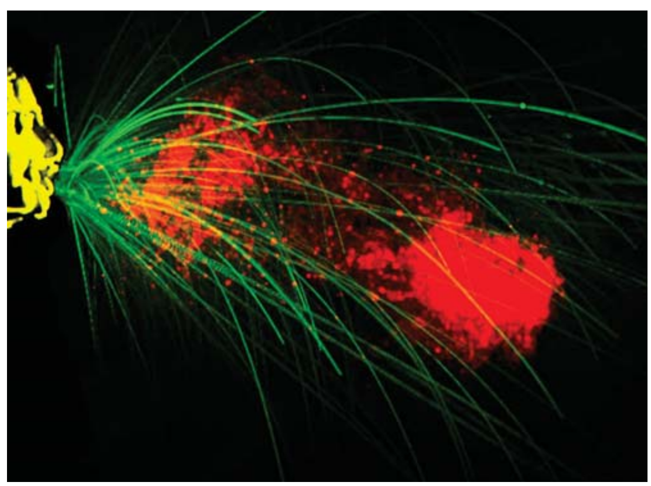

FIGURE 1. VIOLENT EXHALATIONS SUCH AS A SNEEZE release a turbulent cloud of hot, moist air and suspended droplets (red) that can travel the length of most rooms (up to 8 m). The cloud and its payload of saliva and mucus droplets can also linger in the air for as long as 10 minutes. The largest of such drops (green) shoot from the mouth and fall quickly. The gas-phase dynamics enhances the range of suspended droplets by delaying their exit from the cloud. (Image courtesy of Lydia Bourouiba, MIT, from HHMI's Image of the Week: The Anatomy of a Sneeze.)

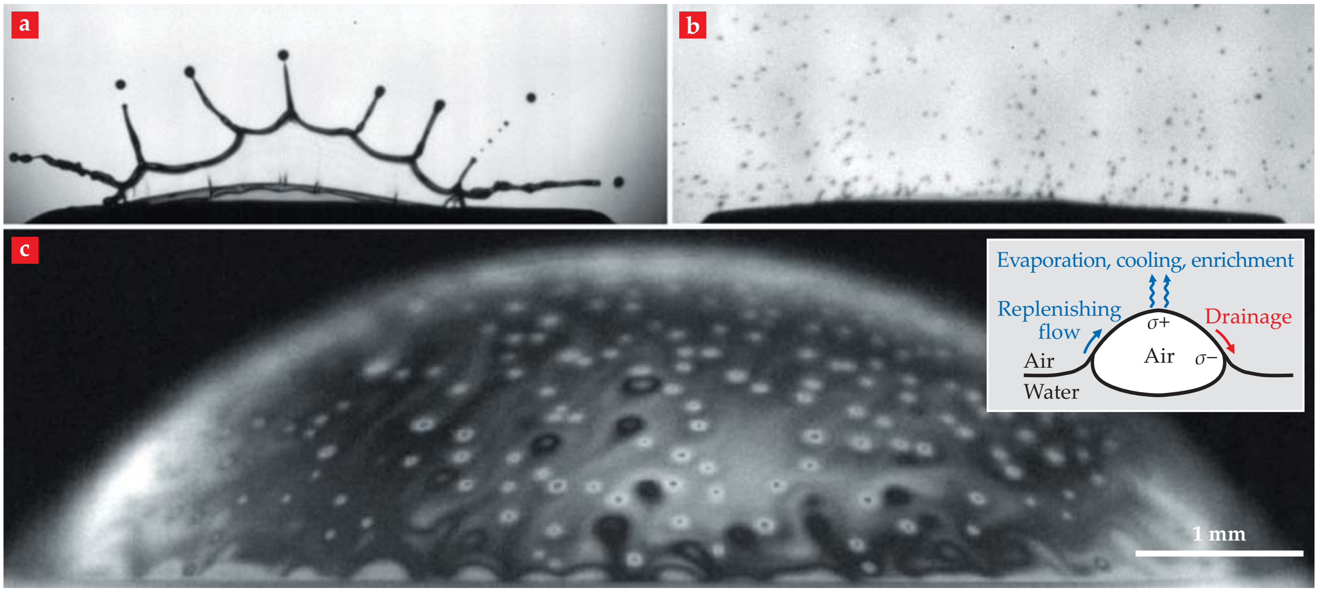

FIGURE 2. TWO BUBBLES BURST ON A WATERY SURFACE, one **(a)** after 3 seconds and the other **(b)** after 55 seconds. The longer-lived bubble, being thinner, spawns some 250 drops when it bursts, whereas the younger one emits less than a dozen. **(c)** An air bubble is shown laden with bacteria. The inset shows that when the surface tension σ of a bubble's apex is higher than that of its base, a replenishing Marangoni flow is established that counters evaporation. (Adapted from S. Poulain, L. Bourouiba, *Phys. Rev. Lett.* **121**, 204502, 2018.)

a given age. The thickening effect is, in fact, general. According to our recent research, any mechanism that produces a surface-tension gradient leaving the base with relatively lower surface tension can dramatically increase the thickness and lifetime of bubbles.

This replenishing effect of evaporation on watery bubbles is, in fact, ubiquitous. It is exacerbated by volatile compounds, such as alcohol (see the article by Roberto Zenit and Javier Rodríguez-Rodríguez, PHYSICS TODAY, November 2018, page 44). The addition of salt also leads to a dramatic illustration of the effect, with important implications for the ocean–atmosphere coupling. In that case, the evaporation enriches the local salt concentration at the apex of each bubble, which further increases σ. The result is bubbles that can stop thinning altogether!

Brimming with bacteria

Freshwater bubbles contaminated with bacteria live much longer than do clean-water bubbles. Indeed, some of them survive for minutes. In our experiments we discovered that bacterial secretions can stabilize those bubbles, which makes them resistant to perturbations that would otherwise pop clean bubbles at much shorter lifetimes. The effect is akin to adding surfactant molecules that stabilize liquid films and give soap bubbles their long lifetimes.

Altough replenishing via upward Marangoni flows is pervasive in clean bubbles, they still continuously thin. However, coated with secretions, bacteria-laden bubbles can reach lifetimes and thicknesses beyond those accessible to clean bubbles. And if such biologically contaminated bubbles survive beyond a critical lifetime, their thinning changes dramatically.

The direct removal of water by evaporation becomes more dominant than the replenishing of water by upward Marangoni flow. That is, in the short term, bubbles become thicker than expected. But beyond a certain age, evaporation thins them out faster than expected. Indeed, drainage-induced thinning is thickness dependent, whereas evaporation-induced thinning is not. Below a critical thickness, the rate of thinning by drainage-dominated dynamics becomes smaller than the rate induced by evaporation.

That subtle competition has important implications. Because they increasingly thin as they age, old and contaminated bubbles produce 10 times as many droplets as clean ones of the same age—potentially hundreds of them from a single bubble. And those droplets are themselves 1/10 as large—down to, on average, 10 μm in radius—and are emitted into the air 10 times as fast (up to 15 m/s) as those of clean bubbles.

Bacterial secretions are known to protect the microorganisms by forming a biofilm—a thick matrix of cells that stick together. But the secretion's effect on bubbles arises even in the absence of a biofilm, and even for common species such as *Escherichia coli*. Despite their tiny size, pathogens cannot be assumed to be passively transported in bubbles and droplets. Indeed, whether they evolved for this purpose or not, when the microorganisms reside on bubbles, they can, in effect, manipulate the underlying interfacial physics to optimize their own dispersal.

Additional resources

▶ L. Bourouiba, "Fluid dynamics of disease transmission and health," in *Research Trends in Biological Fluid Dynamics*, S. Jung et al., eds., US National Committee on Theoretical and Applied Mechanics (2016), p. 11.

▶ L. Bourouiba, J. W. M. Bush, "Drops and bubbles in the environment," in *Handbook of Environmental Fluid Dynamics: Overview and Fundamentals*, H. J. S. Fernando, ed., CRC Press/Taylor & Francis (2013), chap. 32.

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▶ S. Poulain, E. Villermaux, L. Bourouiba, "Ageing and burst of surface bubbles," *J. Fluid Mech.* **851**, 636 (2018).

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